A MARINE INCURSION IN THE LOWER PENNSYLVANIAN TYNEMOUTH CREEK FORMATION, CANADA: IMPLICATIONS FOR PALEOGEOGRAPHY, STRATIGRAPHY AND PALEOECOLOGY

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ABSTRACT

We document the occurrence of a marine bed, and its associated biota, in the Lower Pennsylvanian (Langsettian) Tynemouth Creek Formation of New Brunswick, and discuss its implications for paleogeography, stratigraphy and paleoecology. This is only the second marine interval found in the entire Pennsylvanian fill of the Maritimes Basin of Canada, the other being recently found in the broadly same-age Joggins Formation of Nova Scotia. Evidence for the new marine transgression comprises an echinoderm-rich limestone that infills irregularities on a vertic paleosol surface within the distal facies of a syntectonic fluvial megafan formed under a seasonally dry tropical climate. Gray, platy ostracod-rich shales and wave-rippled sandstone beds that directly overlie the marine limestone contain trace fossils characteristic of the *Mermia* ichnofacies, upright woody trees, and adpressed megafloras. This association represents bay-fills fringed by freshwater coastal forests dominated by pteridosperms, cordaites, and other enigmatic plants traditionally attributed to dryland/upland habitats. The fossil site demonstrates that marine transgressions extended farther inland into the Pangean interior than has previously been documented, and may allow correlation of the Tynemouth Creek and Joggins Formations with broadly coeval European successions near the level of the *Gastrioceras subcrenatum* and *G. listeri* marine bands. It also helps explain the close similarity of faunas between the Maritimes Basin and other paleotropical basins, if transgressions facilitated migration of marine taxa into the continental interior.

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INTRODUCTION

The Maritimes Basin of Atlantic Canada (Fig. 1A) is one of the largest Pennsylvanian depocentres in tropical Pangea, covering 210,000 km^2 (Rehill, 1996). It comprises a complex of small sub-basins separated by basement blocks, each with a distinctive depositional history (van de Poll et al., 1995), developed in a strike-slip context resulting from the oblique convergence of Gondwana with Laurasia (Hibbard and Waldron, 2009). As such, it is recognized as one of the most continental interior basins of tropical Pangea (Gibling et al., 2008). Fluvial deposits dominate the Pennsylvanian fill of the basin, and regional paleocurrent compilations indicate that rivers flowed east to northeast away from the Appalachian Orogen drainage divide towards a 'mid-European sea' (Fig. 2; Gibling et al., 1992; Calder, 1998).

This paper deals with the deposits of the Cumberland sub-basin of northern Nova Scotia and southern New Brunswick (Fig. 1B), which lay in the western part, and judging from regional paleoflow data, the most inland part of the Maritimes Basin complex. This inference is supported by the fact that the Cumberland sub-basin is associated with zones of strong deformation that include strike-slip and thrust faults, along with greenschist facies metamorphism (Nance, 1986, 1987). The Pennsylvanian component of the fill comprises coarse-grained syntectonic alluvium along basin margins (Plint and van de Poll, 1982; Chandler, 1998; Bashforth et al., 2014), and three alternating associations in the basin center: (a) poorly-drained coastal plain deposits with coals, (b) well-drained alluvial deposits with scattered calcrete nodules, and (c) open water deposits with bituminous limestone beds (Davies and Gibling, 2003; Davies et al., 2005). The Cumberland sub-basin also contains important Pennsylvanian fossil sites in the Joggins Formation of Nova Scotia (Falcon-Lang et

al., 2006; Grey and Finkel, 2011) and the Lancaster Formation ('Fern Ledges') of New Brunswick (Falcon-Lang and Miller, 2007; Fig. 1B).

Due to the absence of documented stenohaline faunas in open water facies, the Cumberland sub-basin – and indeed the Maritimes Basin as a whole – was long regarded as a limnic depocentre (Brand, 1994), positioned too far inland to be influenced by glacio-eustatic trangressions that gave rise to the repeated 'marine bands' of northwest Europe (Flint et al., 1995). That view was challenged by the discovery of agglutinated foraminifera at Joggins, which suggested marine influence and a paralic context for the basin (Archer et al., 1995). Shortly thereafter, diverse aquatic faunas (bivalves, ostracods, microconchids, eurypterids, carideans, xiphosurans, fish), long known from the bituminous limestone beds at Joggins and other localities in the Maritimes Basin, were re-evaluated as brackish-marine indicators (Fig. 2; Calder, 1998; Tibert and Dewey, 2006; Falcon-Lang et al., 2006; Prescott et al., 2014; Zaton et al., 2014; Carpenter et al., 2015).

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A major breakthrough was the discovery of petrographic fabrics consistent with stenohaline marine faunas (brachiopods, echinoderms) in limestone beds at four horizons in the lower Joggins Formation, which proved that fully marine transgressions made brief incursions into the basin (Fig. 2; Grey et al., 2011) in the early Langsettian (Utting et al., 2010). Here, we document a second marine occurrence and its biota from a site in southern New Brunswick, and discuss its implications for the paleogeography, stratigraphy and palaeoecology of the Maritimes Basin.

GEOLOGICAL CONTEXT

Evidence for the Pennsylvanian marine transgression documented here was discovered in a coastal section along the Bay of Fundy, on the east side of Emerson Creek, near St Martins, southern New Brunswick, Canada (45°15'37.99''N; 65°46'49.75''W; Fig. 1C). In paleogeographic context, the site is close to the northwestern edge of the Cumberland sub-basin, associated with areas of strong deformation and greenschist facies metamorphism within the orogen (Rast et al., 1984; Nance, 1986, 1987).

Rocks exposed at Emerson Creek belong to the ~ 700 m thick Tynemouth Creek Formation (Cumberland Group), a red-bed-dominated terrestrial succession of Early Pennsylvanian (Langsettian) age based on megafloral and palynofloral content (Fig. 3; Utting et al., 2010; Falcon-Lang et al., 2010; Bashforth et al., 2014). The unit conformably overlies the Boss Point Formation (Plint and van de Poll, 1984; Rygel et al., 2015), and correlates (at least in part) with one or more of the Little River, Joggins and Springhill Mines Formations in the eastern/central part of the Cumberland sub-basin (Fig. 3; Calder et al., 2005; Davies et al., 2005; Utting et al., 2010; Rygel et al., 2014), and the Lancaster Formation further to the west (Falcon-Lang and Miller, 2007).

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In the region of deposition of the Tynemouth Creek Formation, crustal rotation caused by strike-slip movement was restrained by a bend in the Cobequid-Chedabucto Fault, resulting in oblique-slip thrusting along part of the southern edge of the Cumberland sub-basin (Fig. 1B; Plint and van de Poll, 1984; Nance, 1986, 1987). The Tynemouth Creek Formation, which lies to the north of the fault zone and shows a large-scale upward-coarsening trend, was interpreted as an alluvial fan sourced from

this active thrust-front (Plint and van de Poll, 1982; Rast et al., 1984; Plint, 1985). Evidence for syntectonic sedimentation is widespread, including a remarkable series of buried fault scarps that evidently broke the paleosurface (Plint, 1985).

Some of us have recently re-examined the architecture and facies of the Tynemouth Creek Formation (Bashforth et al., 2014), and argued that the predominance of channelized sandstone and pedogenically-altered mudstone in the coarsening-upward succession is best explained in terms of a fluvial megafan model (cf. Hartley et al., 2010; Weissmann et al., 2011). The depositional model envisioned involves proximal gravel-bed fluvial systems that passed basinward into a distributive system of mixed-load fixed-channels and various interfluve facies (Bashforth et al., 2014), with accumulation occurring under a seasonally dry tropical climate (cf. Nichols, 1987; Wells and Dorr, 1987; Hirst, 1991). A modern analogue might be the Kosi megafan of India (Singh et al., 1993). The Emerson Creek section (the focus of this paper) exposes the lowermost part of the Tynemouth Creek Formation (Fig. 3; Falcon-Lang, 2006), and represents the most distal deposits of the fluvial megafan.

EMERSON CREEK SUCCESSION

The study interval at Emerson Creek contains sedimentary and biotic associations that are highly unusual (or possibly unique) in the Tynemouth Creek Formation. The section comprises a predominantly gray, horizontally laminated, coarsening-upward succession, 4.5 m thick, which overlies one paleosol and is capped by a second paleosol (Fig. 4A – B). The interval can only be traced laterally for about 11 m, as it is truncated by normal faults on both sides. However, the beds show no indication of channelization over this distance. Fossils collected from the section, and

146 illustrated here, are accessioned in the collections of the New Brunswick Museum,
147 Saint John (NBMG 16046–16047, 16831–16834, 18584 – 18602).
148
149 Sedimentary Facies
150 Five sedimentary units (1 – 5) are recognized in the studied succession (Fig. 4A – B):
151 Unit 1: The lowermost unit is a ≤ 0.56 m thick paleosol (Fig. 4C) with a
152 hackly fracture, concave-up joints, scattered carbonate nodules, and gray/green or red
153 mottling. The upper surface is highly irregular, with hollows, small downward-
154 tapering cracks, and undercut paleo-ledges.
155 Unit 2: Above the paleosol is a ≤ 0.18 m thick, dark gray limestone that
156 contains a marine fauna (Fig. 4C – D), and which infills the underlying irregular
157 paleo-surface. The limestone shows symmetrical ripples on its upper surface.
158 Unit 3. Overlying the limestone is a sharp-based unit of medium gray
159 laminated siltstone, 1.3 m thick, which contains a few thin beds of dark gray
160 carbonaceous shale. The siltstone unit comprises several stacked, coarsening-upward
161 cycles, rare siderite nodules, symmetrical ripple marks, and ripple cross-lamination.
162 Small woody trees, 30 – 50 mm in diameter, (Fig. 4E) are rooted in growth position at
163 two horizons. Other fossils include indeterminate fish scales, ostracods, trace fossils
164 (Ichnocoenosis A) and megafloral remains (Assemblage 1).
165 Unit 4. Coarsening up from the gray, laminated shales is a succession, 2.1 m
166 thick, dominated by thinly bedded, fine- to medium-grained sandstone (Fig. 4A – B).
167 These beds contain symmetrical ripples, shallow scours, and sediment-cast
168 calamitalean trees in growth position surrounded by mounded bedforms, and
169 megafloral remains (Assemblage 2). Two trace fossil assemblages (Ichnocoenoses B

and C) are present. Some evidence of red/gray pedogenic weathering is observed, manifest as mottling that penetrates downward from surfaces at 3.2 m and 4.3 m in the section (Fig. 4B).

Unit 5. The succession is capped by a red/gray paleosol, ≤ 0.37 m thick, which is not as well-developed as Unit 1, showing color alteration but no pedogenic fabric.

Limestone Petrology and Fauna

The petrology, faunal composition and diagenesis of the limestone bed (Unit 2) were examined using transmitted light microscopy. Percentages of bioclastic, terrigenous, authigenic, and diagenetic components were estimated as rare (< 5%), common (5 – 30%), or abundant (> 30%) using a modal abundance chart. Descriptions and abundances of limestone components are given in Table 1.

In thin section, Unit 2 comprises a fine-grained intraclastic- and bioclastic-rich wackestone (Fig. 5A). Intraclasts include silt- to granule-sized fragments of lime mudstone, and the bioclastic component comprises abundant echinoderm fragments attributed to echinoids, crinoids and/or blastoids (Fig. 5B – C, E), common ostracods (Fig. 5B) and bryozoans (Fig. 5C), and rare pseudopunctate brachiopods (Fig. 5D), gastropods, bivalves, and fish scales. Authigenic and diagenetic components include rare framboidal pyrite, francolite and sucrosic dolomite (Fig. 5F).

Ichnocoenoses

Three ichnocoenoses occur in the study section. Ichnocoenosis A, at 1.9 m in the section (Unit 3; Fig. 4B), occurs in beds of gray, ostracod-rich siltstone with symmetrical ripples that show a microbial ‘elephant skin’ texture (Schieber et al.,

2007) on their upper surfaces (Fig. 6B). The assemblage includes bilobed trails of *Didymaulichnus lyelli*, ≤ 1 mm wide, associated with similar-sized 'bean' shaped *Lockeia siliquaria*, some of which also are bilobed (Fig. 6A), irregular trails of *Helminthoidichnites tenuis*, ≤ 1 mm wide (Fig. 6B), *Arenicolites*, and small, crescent marks of *Selenichnites* isp. (Fig. 6C). Ichnocoenoses B and C, at 2.8 m and 3.9 m in the section (Unit 4; Fig. 4B), respectively, occur in red fine-grained sandstone that locally exhibits small scours or symmetrical ripples. These depauperate assemblages include curved, crosier, a crosier-like burrow that represents one partial whorl (Fig. 6D), bilobed trails of *Didymaulichnus lyelli*, ≤ 2 mm wide, which are somewhat larger than examples in Ichnocoenosis A (Fig. 6E), *Cochlichnus anguineus* (Fig. 6F), and shallowly impressed tetrapod footprints cf. *Baropezia*.

Megafloral Assemblages

Two megafloral assemblages occur in the section. Megafloral Assemblage 1, between 1.2 and 1.7 m in the section (Unit 3; Fig. 4B), occurs in gray shale beds associated with small, upright, woody stems. The relatively diverse assemblage is dominated by adpressed foliage of medullosalean pteridosperms, including *Alethopteris* sp. cf. *A. lancifolia* (n = 5; Fig. 7A), *Paripteris pseudogigantea* (n = 11; Fig. 7B), and *Laveineopteris* sp., cf. *L. hollandica* (n = 2; Fig. 7G), typically preserved as isolated pinnules or small pinnae fragments. Taxa of enigmatic affinity, including cf. *Pseudadiantites rhomboideus* (n = 14; Fig. 7C) and *"Sphenopteris" valida* (n = 1; Fig. 7D) also are present, as are rare lycopsid remains, represented by *Lepidostrobophyllum* sp. (n = 1; Fig. 7F). Megafloral Assemblage 2 occurs in gray shale at 2.3 m in the section (Unit 4; Fig. 4B), and comprises rare and poorly

preserved sphenopsid fragments including *Calamites* sp. (n = 1) and *Annularia* sp., cf. *A. sphenophylloides* (n = 1; Fig. 7E), and cordaitaleans, represented by *Cordaites* sp. leaves (n = 7; Fig. 7H).

INTERPRETATION OF PALEOENVIRONMENT AND ECOSYSTEMS

The ~ 700 m thick Tynemouth Creek Formation is dominated by thick conglomerate and sandstone beds, interpreted as the deposits of braided and fixed-channel belts, and predominantly red mudstone and planar sandstone beds with cumulative Vertisol-like paleosols, interpreted as interfluve deposits, developed within a seasonally dry, syntectonic, fluvial megafan setting (Bashforth et al., 2014). In contrast, the succession at Emerson Creek, which comprises gray, laminated, upward-coarsening beds and contains aquatic (ichno)faunas, was deposited in a standing body of water (Bashforth et al., 2014). Traverses of the entire 17 km long coastal outcrop belt of the Tynemouth Creek Formation reveal only about half a dozen examples of successions that, similarly, might have been deposited under conditions of standing water (Plint and van de Poll, 1982; Falcon-Lang et al., 2010). However, all of these packages represent small lakes and ponds that developed within interfluve hollows (Bashforth et al., 2014). In contrast, the Emerson Creek succession is possibly unique in representing the deposits of a shallow marine embayment.

Marine Bay-Fill Environments

The paleosol at the base of the Emerson Creek section (Unit 1) shows features (concave-up joints, carbonate nodules, mottled red/gray color) that are characteristic

241 of calcic Vertisols formed under a dry subhumid to semi-arid climate (Tandon and
242 Gibling, 1994; Driese et al., 2005).
243 The overlying limestone (Unit 2), which infills the paleotopography,
244 represents a marine incursion that flooded this irregular, seasonally dry terrestrial
245 surface. The presence of echinoderms, brachiopods, and framboidal pyrite indicates
246 deposition under marine salinities (Maliva, 1989; Tucker and Wright, 1990;
247 Schreiber, 2002). The co-occurrence of framboidal pyrite and authigenic francolite
248 further implies that accumulating organic matter was broken down via bacterial
249 sulfate reduction to supersaturate and precipitate phosphate in pore water (Arning et
250 al., 2009; Pufahl, 2010). Mechanically broken, articulated ostracod carapaces, filled
251 with blocky calcite and sucrosic dolomite, suggest alteration during meteoric and
252 shallow burial diagenesis rather than being of paleoenvironmental significance (James
253 and Choquette, 1984; Choquette and Hiatt, 2008).
254 The marine body was extensive because detrital quartz grains are relatively
255 rare, suggesting that the shoreline was distant (Gibling and Kalkreuth, 1991).
256 Nonetheless, the water was shallow given the presence of symmetrical ripples,
257 indicative of formation above normal wave base. The dominance of wave processes is
258 consistent with the microtidal nature of peripheral embayments of the North Variscan
259 Sea inferred from modeling (Wells et al., 2005).
260 Siderite-rich, gray, laminated shale (Unit 3) that coarsens-up into thinly
261 bedded sandstone with symmetrical ripples (Unit 4) records the progradation of
262 coastal sediments during a relative highstand following a marine incursion, with the
263 eventual infilling of the marine embayment. These bodies may have consisted of
264 several small deltaic lobes or thin shoreface units that coalesced to form a single

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coastal package. Red/gray vertic paleosol(s) that cap the succession (Unit 5) mark a resumption of sub-aerial weathering under a seasonal tropical climate and terrestrial conditions more typical of the Tynemouth Creek Formation as a whole.

Significance of Ichnocoenoses

Analysis of the ichnocoenoses helps to improve the resolution of this marine bay-fill interpretation. Ichnocoenosis A, associated with microbially-wrinkled surfaces in gray, siderite-rich shale, records the activity of invertebrate communities in permanently submerged parts of the bay. *Lockeia* and *Didymaulichnus* represent the resting and grazing traces of ostracods, judging by their very small size and bilobed structure. *Helminthoidichnites*, which was produced by a short-bodied animal such as an arthropod given its angular portions, represents another grazing trace (Buatois et al., 1998). *Arenicolites* was the living burrow of an annelid. *Selenichnites* is the resting trace of a xiphosurid (Romano and Whyte, 1987).

Ichnocoenoses B and C, found within symmetrically rippled sandstone with paleosol exposure surfaces, represent the communities of a periodically emergent shoreline. *Cochlichnus* was formed by an animal with an elongate vermiform body that moved in a sinuous fashion, such as an annelid (Hitchcock, 1858), nematode (Moussa, 1970) or possibly an insect larva (Metz, 1987). Also present is a larger type of *Didymaulichnus* formed by a grazing arthropod, and *Spirophycus*-like crozier traces that are very similar to feeding traces produced by extant unionid bivalves in temporarily emergent fluvial bar-top settings (Lawfield and Pickerill, 2006). *Baropezia* are tetrapod tracks (Falcon-Lang et al., 2010), whose faint toe prints suggest wading in shallow water.

289 Collectively, the ichnocoenoses at Emerson Creek are characteristic of the
290 *Mermia* and/or *Scoyenia* ichnofacies (Butaois et al., 1998), which have been
291 considered freshwater associations. However, the associations reported here are
292 unusually depauperate and noteworthy for their association with microbial textures.
293 Similar types of trace fossil assemblages, with limited behavioral repertoires and
294 activities restricted to the epifaunal and shallow infaunal tiers are common in late
295 Paleozoic freshwater environments. They are also more broadly recurrent across
296 space and time in a variety of post-colonization environments, representing the initial
297 exploitation of under-utilized ecospace, a phenomenon termed the 'Déjà vu Effect'
298 (Buatois and Mángano, 2011). While the stratigraphic proximity to marine deposits
299 raises the possibility of some brackish influence, ichnocoenoses lack many
300 characteristic ichnotaxa of coeval brackish deposits (Buatois et al., 2005; Prescott et
301 al., 2014), and we interpret them as near-freshwater associations, more closely
302 associated with overlying terrestrial paleosols (in Units 4 and 5).
303
304 Coastal Vegetation
305 Megafloral assemblages associated with the bay-fill facies shed light on the
306 vegetation of Early Pennsylvanian freshwater forests that fringed the coast. Slender
307 upright trees, rooted in ostracod-rich gray shale (Unit 3), are most likely
308 medullosalean pteridosperms given their close association with the foliage of
309 *Alethopteris*, *Laveineopteris*, and *Paripteris*. These three genera (or their close
310 relatives) have been reconstructed as small trees and shrubs (Pfefferkorn et al., 1984;
311 Shute and Cleal, 2002; Zodrow et al., 2007), consistent with the observed woody
312 stumps, and the same three genera have been interpreted as fringing coastlines in the

313 Lower Pennsylvanian Lancaster Formation ('Fern Ledges') in New Brunswick
314 (Falcon-Lang and Miller, 2007). To what degree this medullosalean-dominated
315 coastal vegetation was saline-tolerant is uncertain (Stull et al., 2012) because, as noted
316 above, associated ichnological evidence for brackish-influence is limited. Other taxa
317 found in the wave-rippled shoreline deposits include calamitaleans and cordaitaleans,
318 both of which are associated with coastlines of broadly the same age, and with closely
319 similar ichnocoenses (Falcon-Lang, 2005, 2015).
320 Still other taxa found in the bay-fill deposits include *Pseudadiantites*
321 *rhomboideus* and *"Sphenopteris" valida*, plants of uncertain affinity that Bashforth et
322 al. (2014) included in their 'enigmatic dryland flora'. Wagner (2001) noted that *P.*
323 *rhomboideus* shares features with some progymnosperms, and *"S." valida* is similar
324 to the putative noeggerathialean *Palaeopteridium michiganensis* (cf. Arnold, 1949;
325 Álvarez-Vázquez, 1995). One hypothesis is that these unusual plants may have been
326 transported into the bay from better-drained, elevated catenas more distant from the
327 coast. Such upland/dryland plants are disproportionately abundant in marine flooding
328 surfaces (Stopes and Watson, 1909; Scott et al., 1997), interpreted to reflect the
329 proximity of upland/dryland environs to the shoreline during times of high sea level
330 (Chaloner, 1958). However, the direct association of the upland/dryland elements
331 with plants typical of Pennsylvanian wetland habitats suggests that the enigmatic
332 floras most likely occupied coastal habitats, as surmised by Bashforth et al. (2014).
333 Many of these upland/dryland taxa have been interpreted as edaphic specialists that
334 occupied thin, nutrient-poor, and alkaline soils (cf. White, 1931; DiMichele et al.,
335 2010), a hypothesis that is consistent with their close association with calcic paleosols
336 at the study site.

DISCUSSION

The paralic context of the Pennsylvanian Maritimes Basin of Atlantic Canada has been recently proved by the discovery of limestone beds that contain stenohaline marine faunas in the Joggins Formation of Nova Scotia (Grey et al., 2011). This discovery is remarkable given that marine bands had never before been recorded in the Pennsylvanian basin fill despite nearly 200 years of intensive study. The marine bed documented herein – the second known example from the Maritimes Basin – has important implications for developing our understanding of the paleogeography, stratigraphy and paleoecology of the basin during the Pennsylvanian. The discovery of a stenohaline biota at the Emerson Creek site is all the more surprising because the limestone is not a prominent, distinctive unit and because it is present within a relatively coarse-grained fluvial megafan succession.

Paleogeographic implications

The Maritimes Basin lay in the collisional zone of Pangea, with marine zones progressively narrowed and eliminated through the late Paleozoic. In such a setting, large low-elevation basins would have become increasingly isolated from ocean circulation, with only occasional marine incursions (Averbuch et al., 2005; Wells et al., 2005), and the youngest long-lived marine interval in the Maritimes Basin is represented by the Mississippian (Visean) Windsor Group (Gibling et al., 2008).

As noted above, compilations of Pennsylvanian fluvial paleocurrent data for the Maritimes Basin indicate that drainage (and hence regional slope) was towards the east and northeast during that time (Gibling et al., 1992), implying that the marine

361 transgression documented here would have advanced in a westerly direction,
362 presumably from a 'mid-European sea' (Fig. 2; Calder, 1998), towards southern New
363 Brunswick (Fig. 8). Being positioned some 120 km southwest of marine deposits of
364 the broadly similar-aged Joggins Formation (Grey et al., 2011), the Emerson Creek
365 marine band of the Tynemouth Creek Formation therefore records the most inland
366 extension of the sea into the Maritimes Basin during the Pennsylvanian. Lying even
367 farther to the west, the Lancaster Formation contains a brackish water assemblage at
368 the 'Fern Ledges' site (Falcon-Lang and Miller, 2007), suggesting that transgressions
369 eventually ran out into freshwater facies (Fig. 8). All three formations are Langsettian
370 in age. Of course, entry points for marine incursions may have been generated or cut
371 off due to tectonic events, and an alternative line of connection closer to the
372 Cumberland sub-basin cannot be ruled out.
373
374 Stratigraphic Implications
375 The general absence of marine bands in the Pennsylvanian fill of the
376 Maritimes Basin (Calder, 1998) has hindered direct correlation of the stratigraphic
377 units with marine-based conodont and goniatite biozones that define IUGS global
378 stage boundaries (Heckel and Clayton, 2006; Heckel et al., 2007). Although index
379 fossils have yet to be recovered from the Emerson Creek marine band, future analyses
380 of this rare occurrence may permit more precise biostratigraphic correlations with
381 other units in the Cumberland sub-basin at Joggins, and more widely across eastern
382 Pangea. Nonetheless, the evidence of sea-level fluctuations alone might also be
383 significant for correlation.

The limestone unit documented here from the lower Tynemouth Creek Formation is the only bed that can, to date, be confidently attributed to a marine incursion. Plint and van de Poll (1982) described rare, 20 – 150 mm thick limestone beds (their facies 6) near Giffin Pond and east and west of Tynemouth Creek, both situated in lower parts of the formation, and interpreted the beds as representing freshwater sediment-starved lakes. However, Plint and van de Poll (1982) briefly remarked that the limestone beds contained ostracods, gastropods, 'spirorbids' (microconchids), and phylloid algae, the latter two components of which are considered brackish to marine indicators (Baars and Torres, 1991; Schultze, 2009; Gierlowski-Kordesch and Cassle, 2015). Despite targeted searches, we were unable to relocate the limestone beds, but these records suggest that additional marine bands may await discovery in the lower part of the formation.

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Marine limestone beds that contain abundant echinoderms and brachiopods also occur at four horizons in the lower 190 m of the 932.4 m thick type section of the Joggins Formation (Grey et al., 2011). Given that both the Tynemouth Creek and Joggins Formations are of general Langsettian age, the occurrence of multiple closely spaced marine bands in the lower part of both units – which are unique in the Pennsylvanian basin fill – may allow sequence stratigraphic correlation of these intervals (Fig. 9).

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In the Joggins Formation, marine bands comprise flooding surfaces that mark the base of sedimentary cycles, which represent the complex interplay of glacio-eustasy and tectonic (Davies and Gibling, 2003). In the Tynemouth Creek Formation, the single occurrence of a marine band occurs above a degraded paleosol surface overlain by an aggradational package of fluvial strata. Such paleosol-bound packages

of aggradational fluvial deposits are a characteristic motif of the Tynemouth Creek Formation (Bashforth et al., 2014) and may be onshore expressions of the sequence stratigraphic cycles documented in more basinal areas at Joggins (Davies and Gibling, 2003) although more work is required to test this hypothesis. In this current case study at Emerson Creek, the maximum flooding surface probably occurs within the marine limestone itself because overlying shales contain near-freshwater ichnotaxa and upright trees. It is possible that progradation of these freshwater coastal plain deposits may have suppressed the development of underlying marine biofacies as demonstrated for Appalachian case studies (Bennington, 1996, 2002).

In the tectonic and paleogeographic setting of the Maritimes Basin, and the Cumberland sub-basin in particular, only the highest amplitude glacio-eustatic sea-level fluctuations might have resulted in marine incursions. In the well-studied Pennsylvanian strata of Britain, which were deposited in a basin undergoing steady thermal subsidence, the most prominent episode of high-amplitude glacio-eustatic marine cycles is in the Yeodonian – early Langsettian interval, whereas only subdued cycles occur in the late Langsettian interval above the *Gastrioceras listeri* Marine Band (Fig. 9; Waters and Condon, 2012). Comparing this pattern with data compilations of marine and brackish bands in the Pennsylvanian fill of the Cumberland sub-basin (Fig. 9), there is no straightforward way to correlate the two successions, presumably due to different paleogeographic settings and basin subsidence rates. However, applying the biostratigraphic framework proposed by Calder et al. (2005), a working hypothesis – requiring testing with conodont-based biozonation – is that the lower Tynemouth Creek and Joggins Formations correlate with marine cycles in the basal and early Langsettian of the British Coal Measures,

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near the level of the regionally important *Gastrioceras subcrenatum* and *G. listeri* marine bands (Fig. 9).

Paleoecologic implications

Establishing a tentative framework for marine connection between western European basins and the Maritimes Basin has important paleoecologic implications. Marine limestone occurrences in the Joggins and Tynemouth Creek Formations both are echinoderm-dominated with a minor ostracod and brachiopod component, but apparently lack goniatites (Grey et al., 2011; this paper). Crinoids with ostracods and productid brachiopods are dominant components of the shallower facies of the *Gastrioceras subcrenatum* marine band of central England (Calver, 1968), whereas goniatites were restricted to deeper water settings. Echinoderm-dominance in marine bands in the Maritimes Basin is therefore consistent with paleogeographic interpretations as peripheral embayments of European marine bands. Distal dispersal of echinoderms and brachiopods would have been facilitated through their planktonic larval stage and circulation patterns (Wells et al., 2005).

More broadly, systematic studies of aquatic faunal groups (fish, bivalves, ostracods, microconchids, eurypterids, carideans, xiphosurans) found in the Pennsylvanian fill of the Maritimes Basin have emphasized their unusually cosmopolitan and euryhaline nature (Calder, 1998; Zaton et al., 2014; Carpenter et al., 2015), showing strong similarities with same-aged faunas of both western and eastern Pangea. The occurrence of widespread but cryptic marine transgressions throughout the Maritimes Basin is an obvious mechanism for the dispersal of aquatic biota, and

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455 helps explain the compositional congruity of these faunas both west and further east
456 of the Appalachian drainage divide (Falcon-Lang et al., 2006).
457
458 CONCLUSIONS
459 1. We report only the second confirmed example of a stenohaline marine suite in
460 the Pennsylvanian fill of the Maritimes Basin of Atlantic Canada, despite
461 nearly 200 years of investigation in the succession.
462 2. The marine band, which comprises an echinoderm-rich wackestone occurs in
463 the distal deposits of a seasonally-dry, syntectonic fluvial megafan represented
464 by the Lower Pennsylvanian (Langsettian) Tynemouth Creek Formation of
465 southern New Brunswick.
466 3. Pteridosperm- and cordaite-rich plant communities, interspersed with plants of
467 enigmatic affinity, fringed the margins of this marine embayment, rooted in
468 shallow, coastal muds that probably were of near-freshwater salinities based
469 on the depauperate ichnofaunas.
470 4. A stratigraphic hypothesis that requires testing with conodont-based
471 biozonation is that the marine band correlates with similar units in the
472 Langsettian Joggins Formation of Nova Scotia, and with levels near the
473 *Gastrioceras subcrenatum* and *G. listeri* marine bands in western Europe.
474 5. Recognition of marine transgressions in the Maritimes Basin helps to explain
475 the congruence of aquatic faunas with those seen in other paralic basins of
476 tropical Pangea.
477
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762

762 FIGURE CAPTIONS

763 **FIGURE 1—**Location details and geological context of study site. A., Southwestern
764 outcrop belt of the Maritimes Basin of Atlantic Canada. B., Cumberland sub-basin
765 of central Nova Scotia and southern New Brunswick on the edge of the
766 Appalachian Orogen. C., Outcrop belt of the Pennsylvanian (Langsettian)
767 Tynemouth Creek Formation of southern New Brunswick. Note position of the
768 study locality at Emerson Creek on the southwestern margin of the coastal
769 exposure. (After van de Poll et al., 1995; Plint and van de Poll, 1982; Falcon-Lang,
770 2006; Bashforth et al., 2014).

771 **FIGURE 2—**Paleogeographical setting of the 'brackish seas' developed at Joggins,
772 Nova Scotia (After Falcon-Lang, 2005). A., Global paleogeography showing
773 putative connection of Maritimes Basin to the Tethys Ocean during marine
774 maximum flooding. B., Reconstruction of central tropical Pangaea at maximum sea
775 level, showing an extensive brackish embayment into the Maritimes Basin.
776 Transgression direction inferred from the inverse of fluvial paleocurrents (Gibling
777 et al. 1992).

778 **FIGURE 3—**Stratigraphic relationships of Lower Pennsylvanian (Langsettian)
779 lithostratigraphic units of the Cumberland sub-basin, Nova Scotia and New
780 Brunswick (after Davies et al., 2005; Falcon-Lang, 2006; Bashforth et al., 2014),
781 and their approximate relationship to European regional chronostraphic
782 boundaries.

783 **FIGURE 4—**Geology of the study locality at Emerson Creek. A., Photograph of the
784 measured section lying between two paleosols, with location of ichnocoenoses
785 marked as IA, IB and IC. Logged section in Fig. 4B shown by line. Scale: hammer

(0.4 m long). B., Stratigraphic log of 4.5 m thick succession that contains marine limestone (Unit 2) near base. C., Limestone (Unit 2) infilling irregularities on paleosol surface (Unit 1) at 0.5 m on log. D., Gastropods in limestone (Unit 2) at 0.6 m on log. Scale: 5 mm. E., Base of a small (gymnosperm?) stem with roots at 1.2 m on log (Unit 3).

FIGURE 5—Micrographs of shelly fauna and other features in limestone at 0.6 m on log in Fig. 4B. All images in plane-polarized light. A., Fine-grained, ostracod-rich, intraclastic wackestone; scale: 1 mm. B., Articulated ostracod (o) infilled with blocky calcite. In addition to carbonate intraclasts and lime mud, the matrix contains rare echinoid spines (s) and sucrosic dolomite rhombs (d); scale: 100 µm. C., Bryozoan fragment (b) and echinoderm clasts (e); scale: 200 µm. D., Pseudopunctate brachiopod shell; scale: 100 µm. E., Echinoderm fragments (e), scale: 100 µm. F., Framboidal pyrite (f). Shell fragments are ostracods; scale: 200 µm.

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FIGURE 6—Ichnocoenoses at the Emerson Creek site. All images show the base of bedding surface except (C), which shows broken surface. A., Small bilobed trails of *Didymaulichnus lyelli* (1) and similar-sized 'bean' shaped *Lockeia*, some of which are bilobed (2), NBMG 16047, Ichnocoenosis A, scale: 5 mm. B., Irregular trails of *Helminthoidichnites tenuis*, which move up and down relative to bedding. Some surfaces show microbial wrinkling (arrow), Ichnocoenosis A, NBMG 16046, scale: 5 mm. C., *Selenichnites* isp., Ichnocoenosis A, not collected, scale 10 mm. D., Crosier-like burrow, Ichnocoenosis B, not collected, scale: 5 mm. E., Small bilobed trails of *Didymaulichnus lyelli*, but somewhat larger than in (A),

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Ichnocoenosis C, not collected, scale: 5 mm. F., *Cochlichnus* isp., Ichnocoenosis C, not collected, scale: 5 mm.

FIGURE 7—Megafloral remains at the Emerson Creek site (in part, EC-1 of Bashforth et al., 2014). A., *Alethopteris* sp. cf. *A. lancifolia*, specimen on right, not collected, scale: 5 mm. B., *Paripteris pseudogigantea*, NBMG16831, scale: 4 mm. C., cf. *Pseudadiantites rhomboideus*, NBMG16833B, scale: 7 mm. D., *"Sphenopteris" valida*, not collected, scale: 6 mm. E., *Annularia* sp. cf. *A. sphenophylloides*, not collected, scale: 10 mm. F., *Lepidostrobophyllum* sp., NBMG16834, scale: 10 mm. G., *Laveineopteris* sp. cf. *L. hollandica*, not collected, scale: 10 mm. H., *Cordaites* sp. (?), not collected, scale: 25 mm.

FIGURE 8—Schematic block diagram illustrating a marine incursion into the Cumberland sub-basin of central Nova Scotia and southern New Brunswick (after Falcon-Lang, 2006). Arrows show direction of transgression. Red dotted line delineates the current coastline of the Bay of Fundy.

FIGURE 9—Patterns of marine and brackish transgressions in the Cumberland sub-basin (compiled from various paleontological data in Dawson, 1868; Calder et al., 2005; Falcon-Lang and Miller, 2007; Grey et al., 2011; Rygel et al., 2014, 2015; Carpenter et al., 2015; this paper) compared with patterns in the cratonic Pennine Basin of the UK (Waters and Condon, 2012). The relative extent (area covered in the Pennine Basin) and salinity of marine incursion is shown. Key: transgressions – blue, fully marine; purple, brackish; dotted purple, possible brackish. In the Pennine Basin dataset, salinity of brackish bands is inferred to increase from (E) *Estheria* band to (F) foraminifer band to (L) *Lingula* band to (B) brachiopod band (Waters and Condon, 2012).

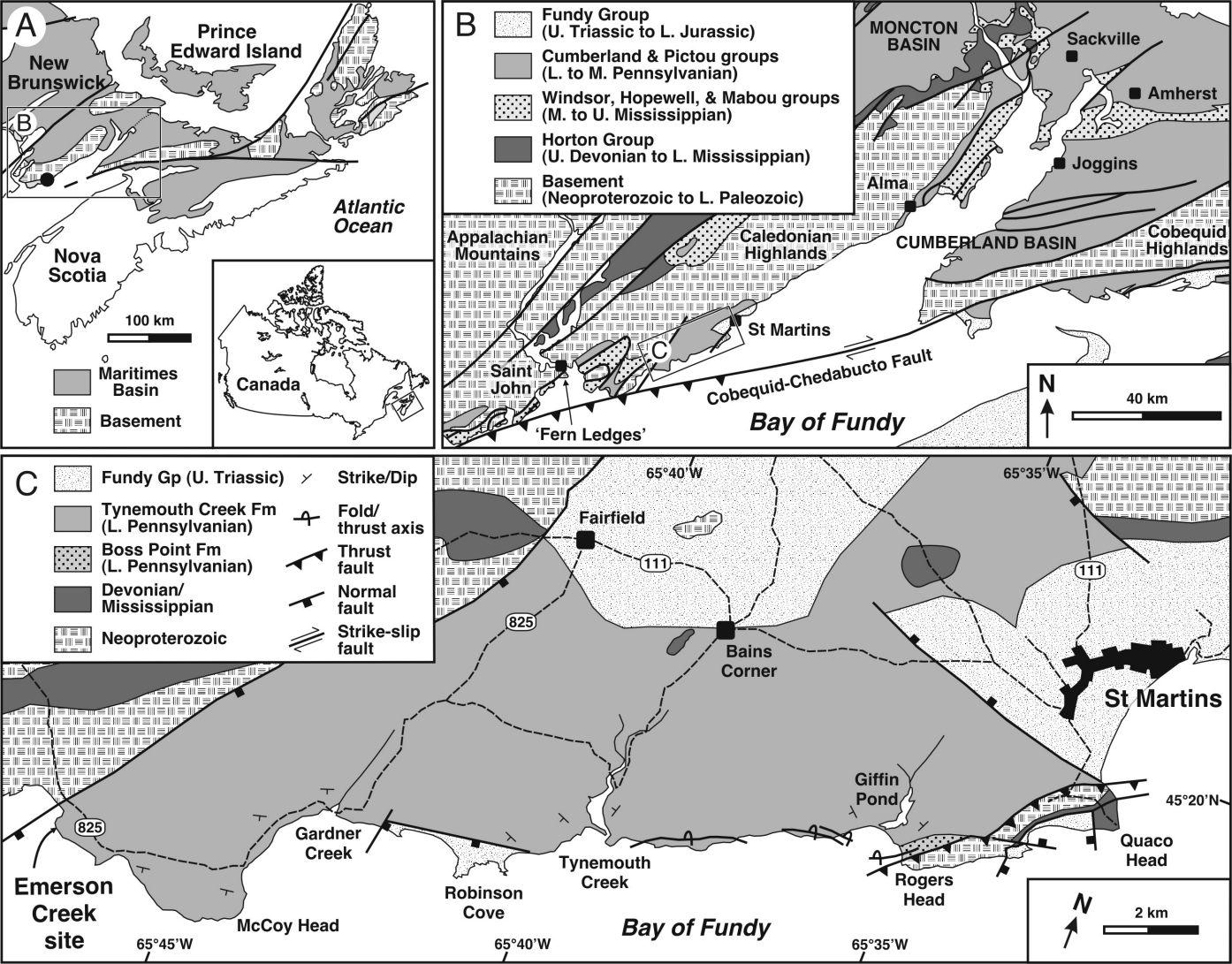
833

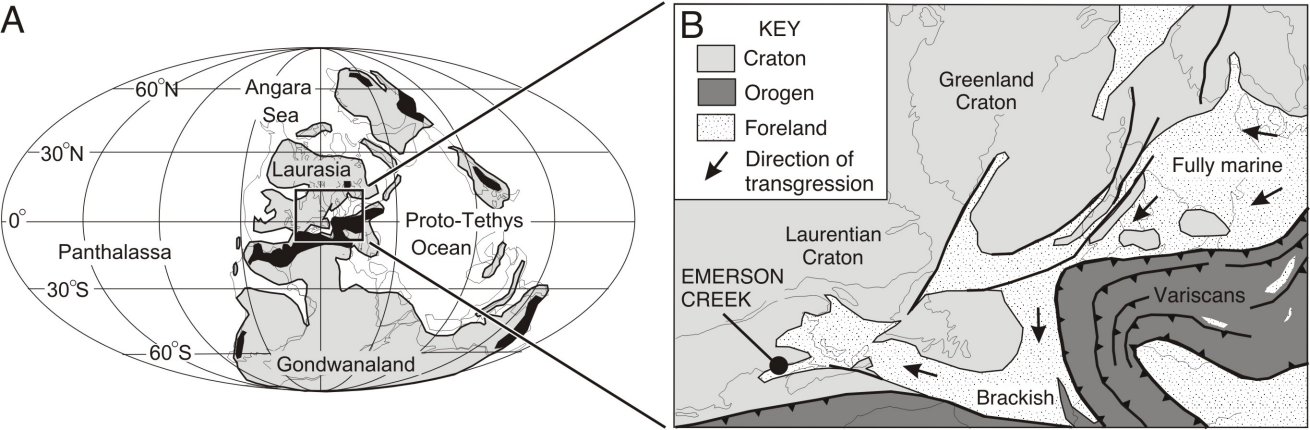
834 TABLE CAPTION

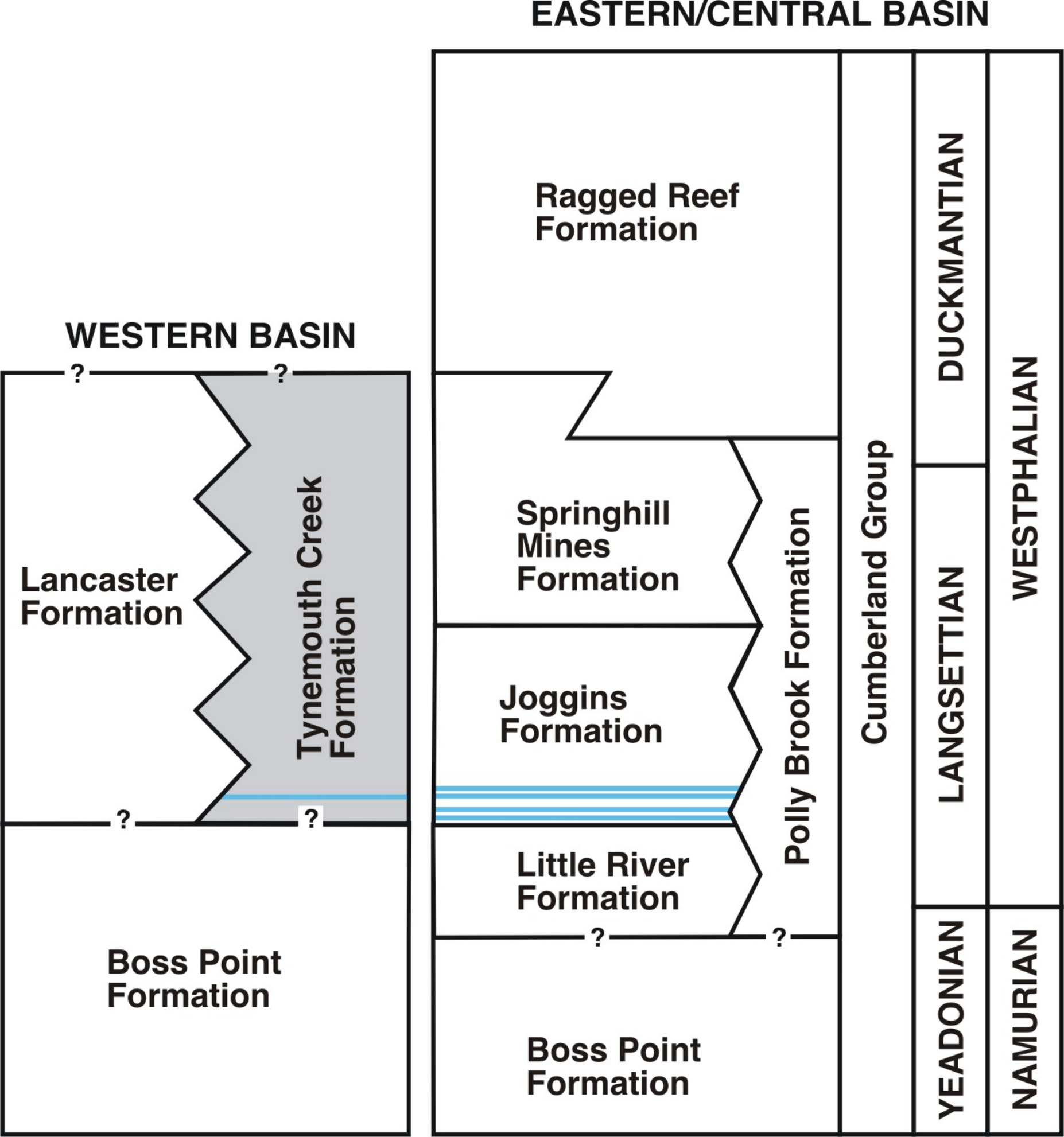
835 **TABLE 1—**Limestone petrography at Emerson Creek locality, southern New

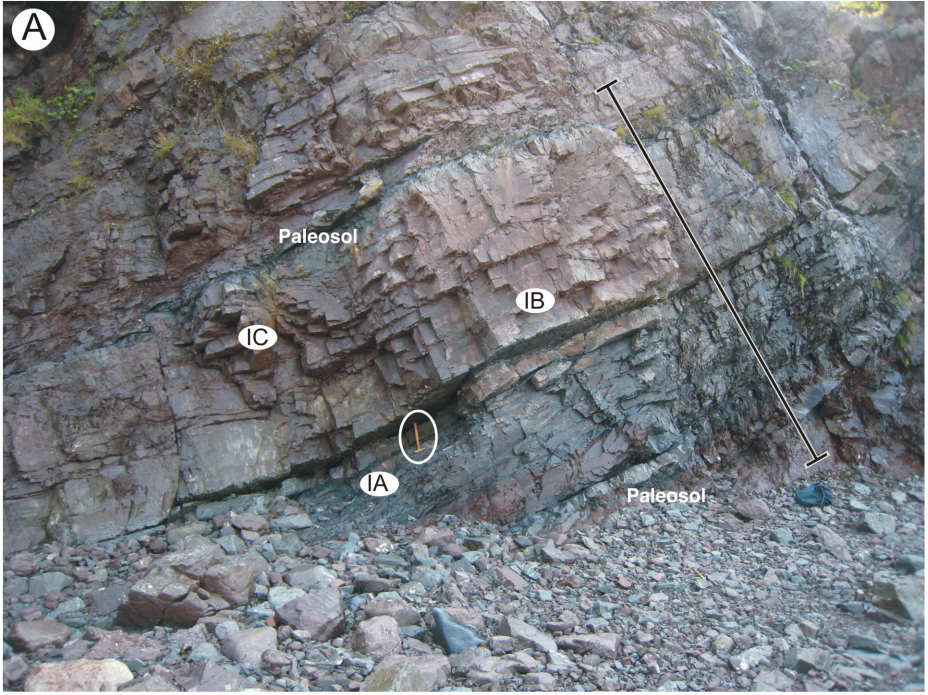
836 Brunswick. Abundance index: rare (< 5%), common (5 – 30%), abundant (> 30%).

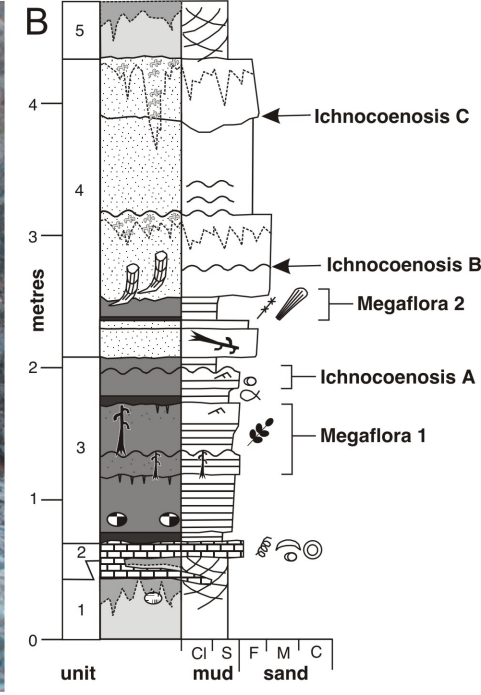
837

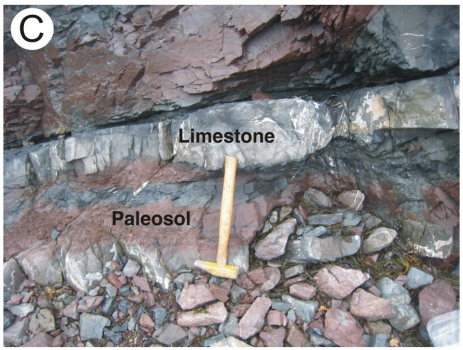

A
New Brunswick
Prince Edward Island
B
Atlantic Ocean
Nova Scotia
100 km
Maritimes Basin
Basement
Canada
B
Fundy Group (U. Triassic to L. Jurassic)
Cumberland & Pictou groups (L. to M. Pennsylvanian)
Windsor, Hopewell, & Mabou groups (M. to U. Mississippian)
Horton Group (U. Devonian to L. Mississippian)
Basement (Neoproterozoic to L. Paleozoic)
MONCTON BASIN
Sackville
Amherst
Joggins
Alma
CUMBERLAND BASIN
Cobequid Highlands
Appalachian Mountains
Caledonian Highlands
St Martins
C
Saint John
'Fern Ledges'
Cobequid-Chedabucto Fault
Bay of Fundy
N
40 km
C
Fundy Gp (U. Triassic)
Tynemouth Creek Fm (L. Pennsylvanian)
Boss Point Fm (L. Pennsylvanian)
Devonian/ Mississippian
Neoproterozoic
Strike/Dip
Fold/ thrust axis
Thrust fault
Normal fault
Strike-slip fault
65°40'W
65°35'W
Fairfield
111
825
Bains Corner
St Martins
Giffin Pond
45°20'N
Quaco Head
Gardner Creek
Tynemouth Creek
Rogers Head
Emerson Creek site
Robinson Cove
McCoy Head
65°45'W
65°40'W
Bay of Fundy
65°35'W
N
2 km

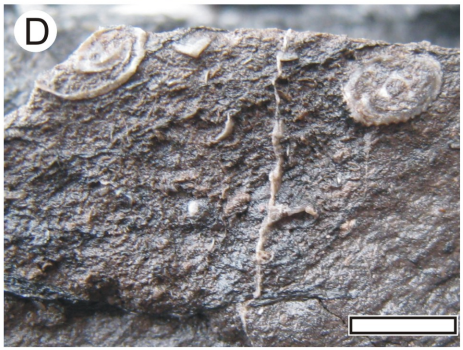

A
60°N
30°N
0°
30°S
60°S
Angara
Sea
Laurasia
Proto-Tethys
Ocean
Panthalassa
Gondwanaland
B
KEY
Craton
Orogen
Foreland
Direction of
transgression
Greenland
Craton
Fully marine
Laurentian
Craton
EMERSON
CREEK
Variscans
Brackish

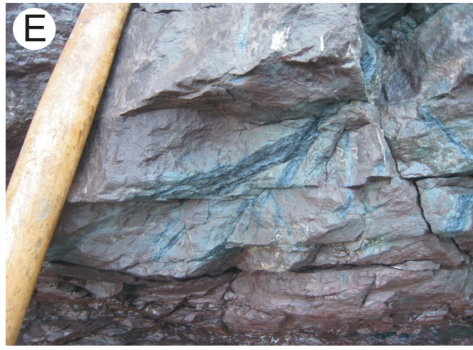

EASTERN/CENTRAL BASIN
WESTERN BASIN
Ragged Reef Formation
Springhill Mines Formation
Joggins Formation
Little River Formation
Boss Point Formation
Lancaster Formation
Tynemouth Creek Formation
Boss Point Formation
Polly Brook Formation
Cumberland Group
DUCKMANTIAN
LANGSETTIAN
YEADONIAN
WESTPHALIAN
NAMURIAN
?











Lithology

- Limestone
- Dark gray mudstone
- Medium gray mudstone
- Green-gray mudstone
- Red mudstone
- Sandstone

Sedimentary structures

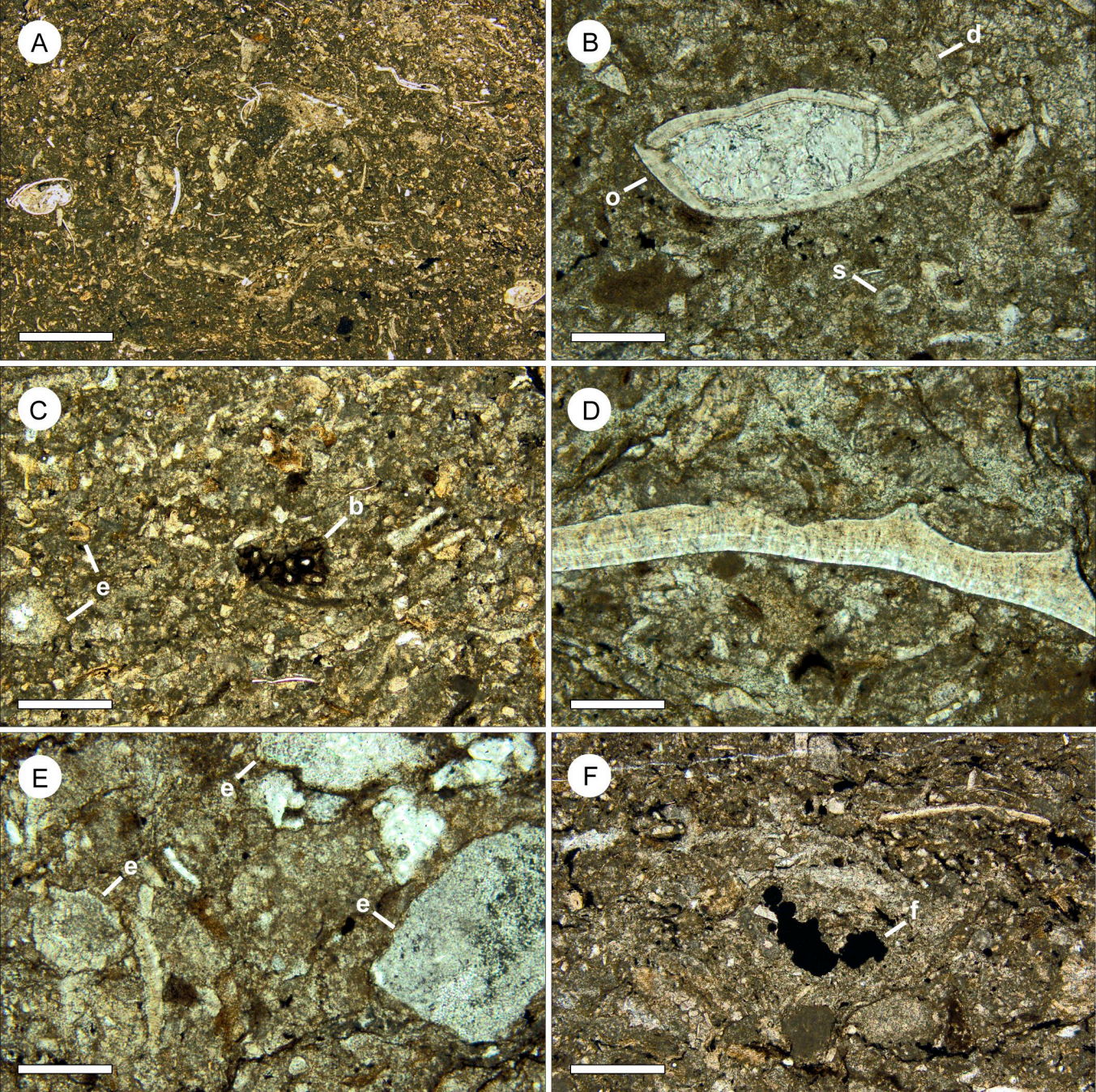
- Siderite nodules
- Calcrete nodules
- Green-gray/red mottles
- Ripple cross-lamination
- Horizontal lamination
- Symmetrical ripple marks
- Concave-up joint sets

Megafloral remains

- Cordaites
- Calamitalean foliage
- Calamitalean axis (upright)
- Woody tree (upright)
- Pteridosperms (and allies)
- Indeterminate rootlets

Faunal remains

- Ostracods
- Fish
- Brachiopods
- Gastropods
- Echinoderms


A
B
d
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C
b
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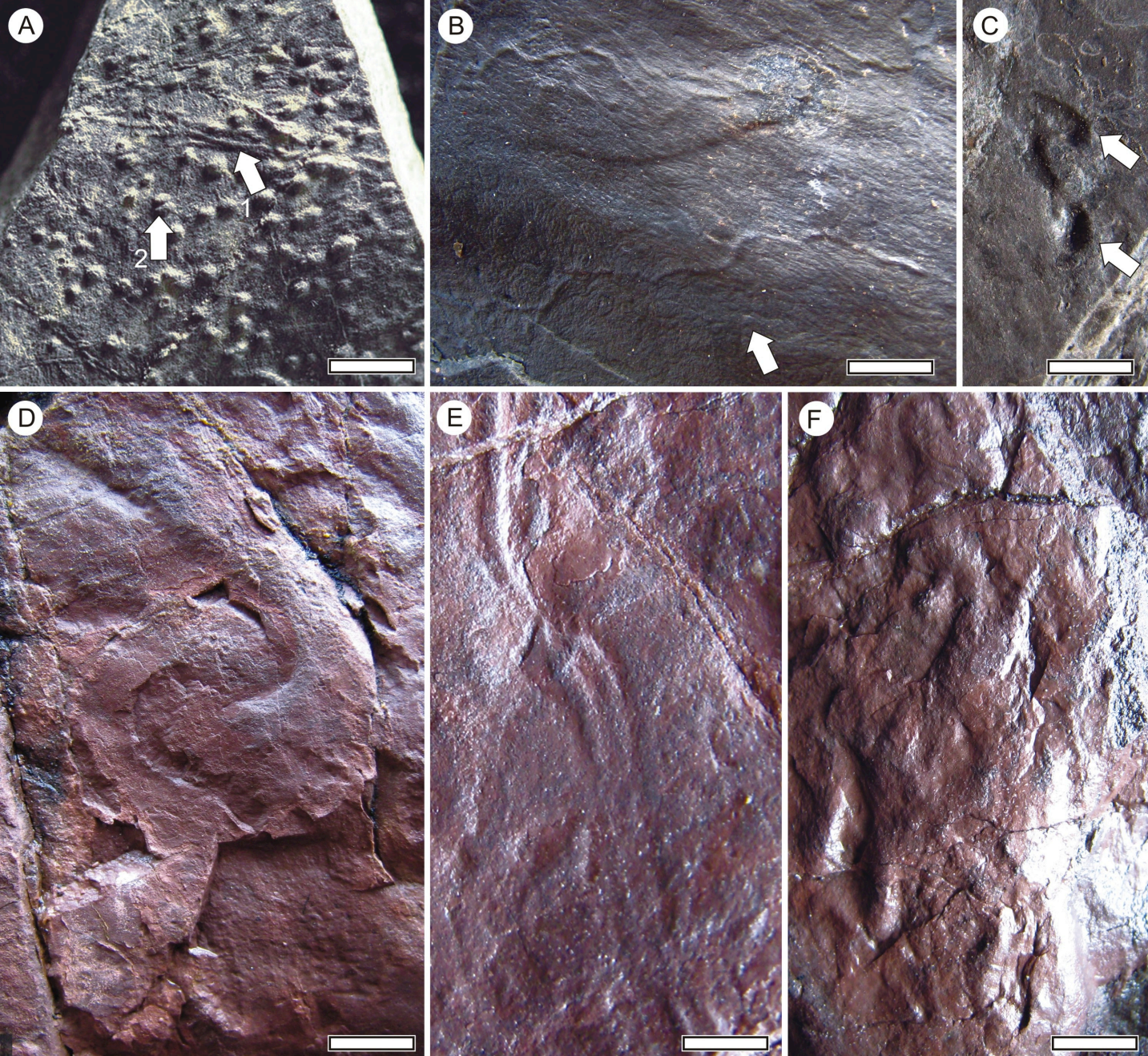
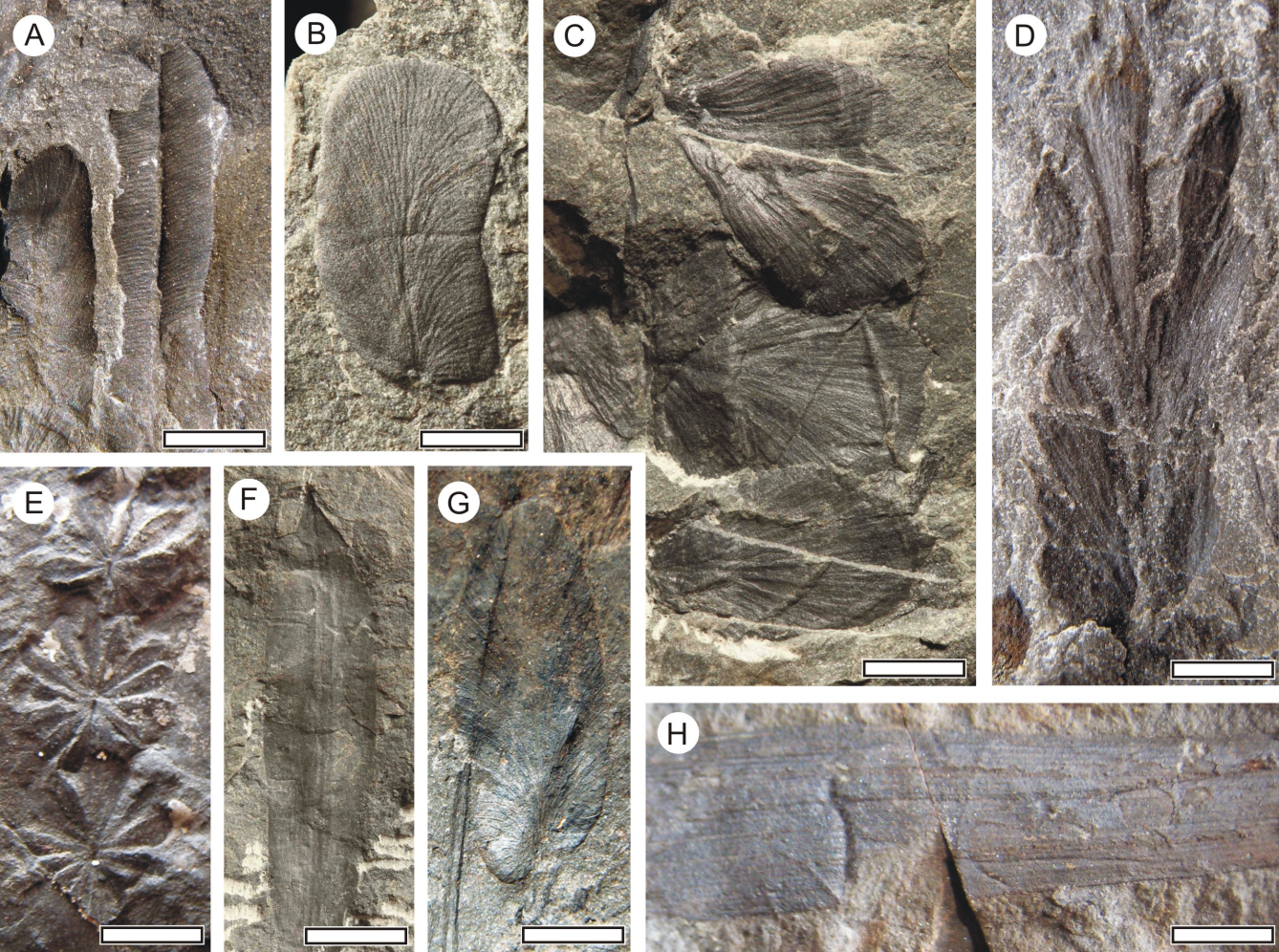
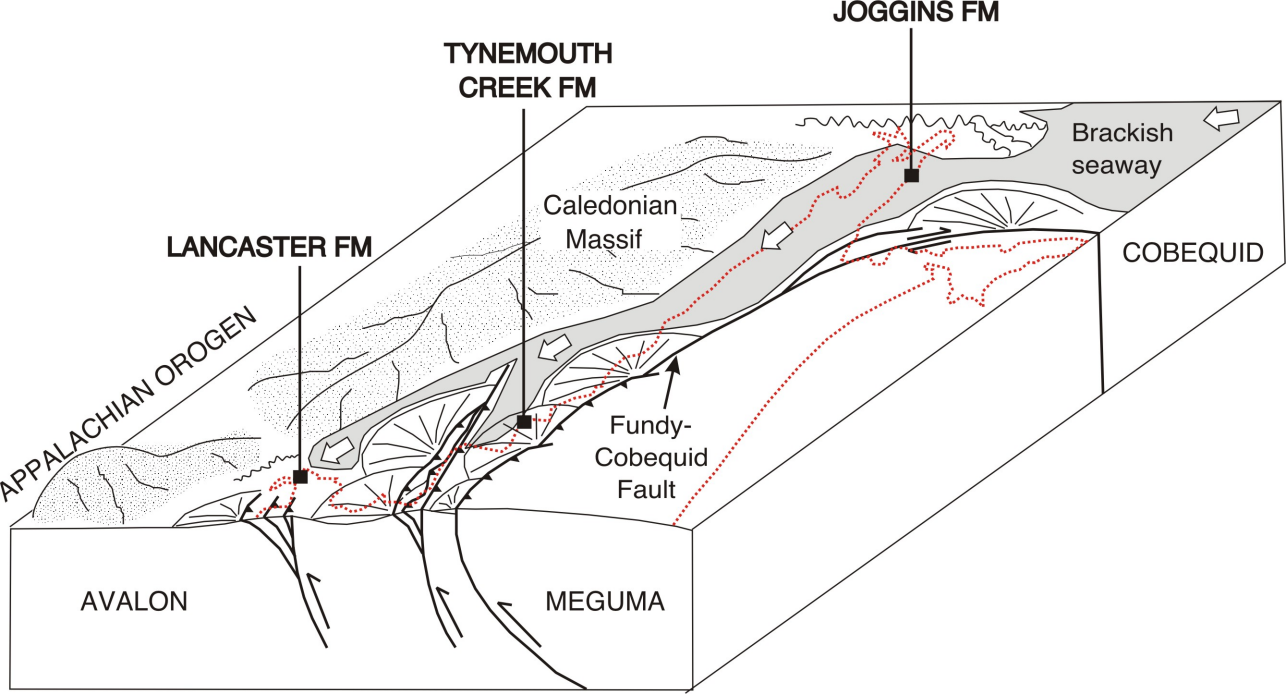
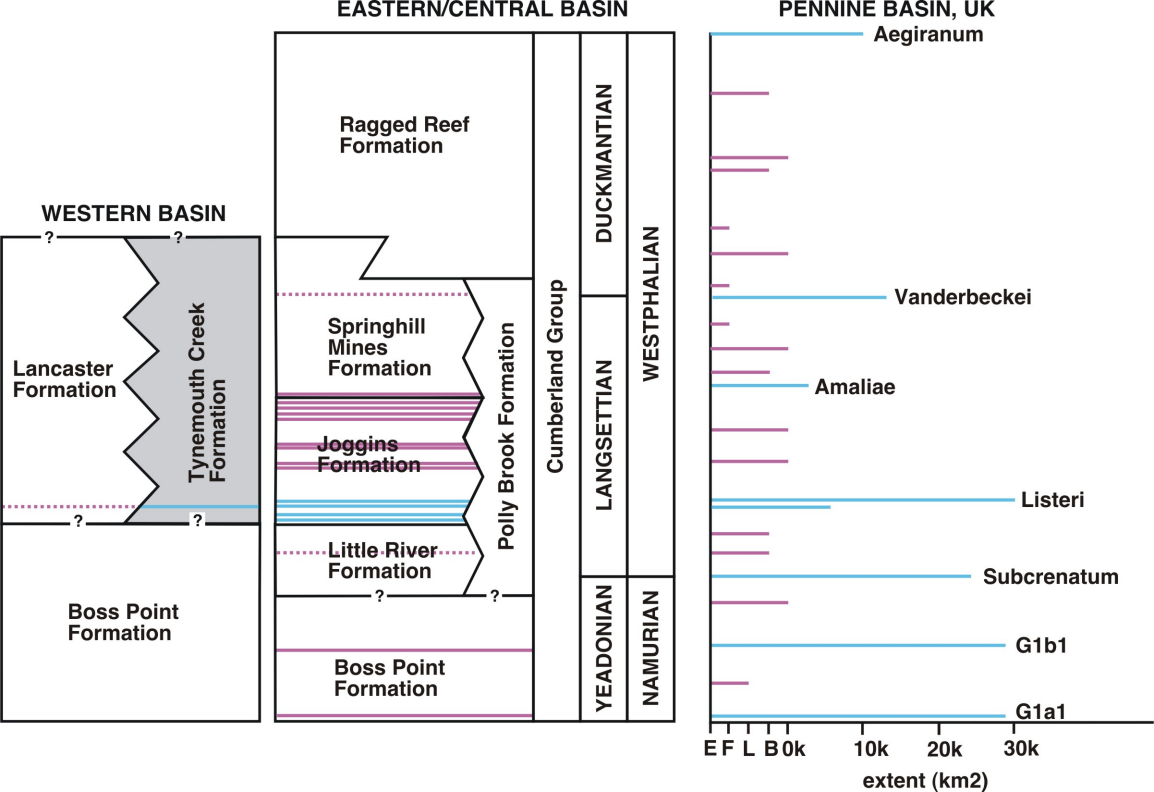
F
f


A
1
2
B
C
D
E
F


A
B
C
D
E
F
G
H


JOGGINS FM
TYNEMOUTH CREEK FM
LANCASTER FM
Brackish seaway
Caledonian Massif
COBEQUID
APPALACHIAN OROGEN
Fundy-Cobequid Fault
AVALON
MEGUMA


EASTERN/CENTRAL BASIN
PENNINE BASIN, UK
WESTERN BASIN
Ragged Reef Formation
Springhill Mines Formation
Joggins Formation
Little River Formation
Polly Brook Formation
Cumberland Group
DUCKMANTIAN
LANGSETTIAN
YEADONIAN
WESTPHALIAN
NAMURIAN
Lancaster Formation
Tynemouth Creek Formation
Boss Point Formation
Boss Point Formation
Aegiranum
Vanderbeckei
Amaliae
Listeri
Subcrenatum
G1b1
G1a1
E F L B 0k
10k
20k
30k
extent (km2)

Composition	Frequency	Description
(1) Detrital component		
lime mud	abundant	matrix
intraclasts	common	silt to granule-size lime mudstone clasts
detrital quartz	common	sub-rounded to angular, silt to fine-grained sand
detrital chert	rare	rounded, silt size grains
muscovite	rare	
(2) Bioclastic component		
echinoderms	abundant	echinoids, crinoids and/or blastoids; silt to fine-grained sand size fragments with unit extinction; some with epitaxial cement
ostracods	common	mostly disarticulated and fragmented, but rarely articulated; articulated carapaces occluded with blocky calcite
bivalves	rare	recrystallized shell fragments
brachiopods	rare	unrecrystallized, pseudopunctate shell fragments
bryozoans	rare	fine-grained sand size fragments
echinoid spines	rare	characteristic radial arrangement of pores within individual spines
fish scales	rare	individual scales are honey-brown color and slightly abraded
gastropods	rare	recrystallized shell fragments
Authigenic component		
francolite	rare	apatite peloids; characteristic honey-brown color
framboidal pyrite	rare	
Diagenetic component		
sucrosic dolomite	rare	silt-sized, sucrosic dolomite rhombs

Abundance Index: rare (1 – 5%); common (6 – 30%); abundant (> 30%)